Robotic Path Planning for Non-Destructive Testing of Complex Shaped Surfaces

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Abstract. The requirement to increase inspection speeds for non-destructive testing (NDT) of composite aerospace parts is common to many manufacturers. The prevalence of complex curved surfaces in the industry provides significant motivation for the use of 6 axis robots for deployment of NDT probes in these inspections. A new system for robot deployed ultrasonic inspection of composite aerospace components is presented. The key novelty of the approach is through the accommodation of flexible robotic trajectory planning, coordinated with the NDT data acquisition. Using a flexible approach in MATLAB, the authors have developed a high level custom toolbox that utilizes external control of an industrial 6 axis manipulator to achieve complex path planning and provide synchronization of the employed ultrasonic phase array inspection system. The developed software maintains a high level approach to the robot programming, in order to ease the programming complexity for an NDT inspection operator. Crucially the approach provides a pathway for a conditional programming approach and the capability for multiple robot control (a significant limitation in many current off-line programming applications). Ultrasonic and experimental data has been collected for the validation of the inspection technique. The path trajectory generation for a large, curved carbon-fiber-reinforced polymer (CFRP) aerofoil component has been proven and is presented. The path error relative to a raster-scan tool-path, suitable for ultrasonic phased array inspection, has been measured to be within ± 2mm over the 1.6 m^2 area of the component surface.

INTRODUCTION

In civil aerospace manufacturing, the increasing deployment of composite materials demands a high integrity and traceability of NDT measurements. Modern components increasingly present challenging shapes and geometries for inspection. Using traditional manual inspection approaches produces a time-consuming bottleneck in industrial production environments [1] and hence provides the fundamental motivation for increased automation.

The combined use of Modern Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) now allows large items to be produced easily from one piece of raw material (either through traditional subtractive approaches, or with more recent additive manufacturing processes [2]). As a result, large components with complex geometries are becoming very common in modern structures, and the aerospace industry is a typical field, where wide complex shaped parts are very frequently used. Moreover the use of composite materials, which are notoriously challenging to inspect [3], is becoming widespread in the construction of new generations of civilian aircraft. To cope with future demand projections for these operations, it is therefore essential to overcome the current NDT bottleneck.

A fundamental issue with composites manufacturing compared to conventional light alloy materials lies in the process variability. Often parts that are designed as identical, will have significant deviations from CAD, and also

suffer from inherent but different part to part spring-back out of the mould. This presents a significant challenge for precision NDT measurement deployment which must be flexible to accommodate these manufacturing issues. For these reasons, NDT inspection is often performed manually by technicians who typically have to move appropriate probes over the contour of the sample surfaces. Manual scanning requires trained technicians and results in a very slow inspection process for large samples. The repeatability of a test can be challenging in structures where complex setups are necessary to perform the inspection (e.g. orientation of the probe, constant standoff, etc.) [4]. While manual scanning may remain a valid approach around the edges of a structure, or the edges of holes in a structure, developing reliable automated solutions has become an industry priority to drive down inspection times. The fundamental aim of automation within the inspection process is to minimize downtimes due to the higher achievable speed, and in parallel to carry out 100% inspection coverage of the sample, including all edge areas.

Semi-automated inspection systems have been developed to overcome some of the shortcomings with manual inspection techniques, using both mobile and fixed robotic platforms. The use of linear manipulators and bridge designs has for a number of years provided the most stable conditions in terms of positioning accuracy [5, 6]. The use of these systems to inspect parts with noncomplex shapes (plates, cylinders or cones) is widespread; typically, they are specific machines which are used to inspect identically shaped and/or sized parts.

More recently, many manufacturers of industrial robots have produced robotic manipulators with excellent positional accuracy and repeatability. In the spectrum of robot manipulators, some modern robots have suitable attributes to develop automated NDT systems and cope with the challenging situations sought by the aerospace industry [7]. They present precise mechanical systems, the possibility to accurately calibrate each joint, and the ability to export positional data at frequencies up to 500Hz.

Some applications of 6-axis robotic arms in the NDT field have been published during the last few years and there is a growing interest in using such automation solutions with many manufacturers within the aerospace sector [1, 7-10]. Despite these previous efforts, there remain challenges to be addressed before fully automated NDT inspection of composite parts becomes commonplace. The key challenges include generation and in-process modification of the robot tool-path, high speed NDT data collection, integration of surface metrology measurements, and overall visualization of measurement results in a user friendly fashion. Collaborations driving this vision include the IntACom project, developed by TWI Technology Centre (Wales) on behalf of their sponsors over a period of 3 years. The project objective has been to achieve a fourfold increase in the throughput of aerospace components [1].

Additionally the UK RCNDE consortium conducts research into integration of metrology with NDT inspection [11, 12]. Both these consortia have identified the requirement for optimal tool path generation over complex curved surfaces. The current paper describes a novel approach to flexible robotic toolpath generation using a purposely developed MATLAB based path-planning software platform.

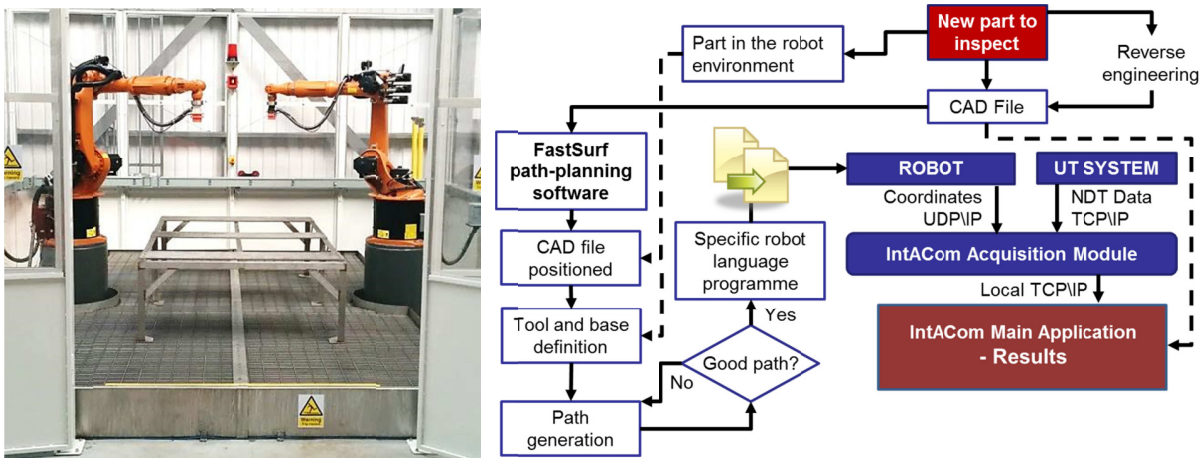
INVESTIGATED PATH PLANNING APPROACHES FOR NDT APPLICATIONS

Traditional Approach

Six-axis robotic arms have traditionally been used in production lines to move the robot end-effector from one position to a new position for repetitive assembly and welding operations. In this scenario, where the exact trajectory between two points in the space is not too important, the teach pendant of a robot is used to manually move the end-effector to the desired position and orientation at each stage of the robot task. Relevant robot configurations are recorded by the robot controller and a robot program is then written to command the robot to move through the recorded end-effector postures. More recently, accurate mechanical joints and control units have made industrial robotic arms flexible and precise enough for finishing tasks in manufacturing operations [13]. Robotic manipulators are highly complex systems and the trajectory accuracy of a machining tool has a huge impact on the quality and tolerances of the finished surfaces. As a result, many software environments have been developed by non-robot manufacturers, academic researchers and also by the robot manufacturers themselves, in order to help technicians and engineers to program complex robot tasks [14]. The use of such software platforms to program robot movements is known as Off-Line Programming (OLP). It is based on the 3D virtual representation of the complete robot work cell, the robot end-effector and the samples to be manipulated or machined. OLP was first achieved within the

IntACom project using commercial robotic simulation and programming software. The chosen software was CENIT-FastSurf [15], based on the Delmia platform (Dassault Systems) [16].

Figure 1 shows the IntACom robot cell and the schematic representation of the originally developed robotic inspection procedure. Robot manipulators and modern Ultrasound Testing (UT) acquisition instruments have a strong potential to give a great deal of flexibility for fast and effective NDT inspections of large curved samples. However it was necessary to develop suitable software to integrate the robot manipulators and the ultrasound instruments, through encoding the ultrasound signals with the positional information coming from the robot controller. The IntACom software has a fundamental role within the inspection procedure. The main application, developed in the C# programming language, controls the GUI and behaves as a server application. The C++ language was chosen to write the acquisition module. Unlike C#, C++ is suitable to develop real-time data acquisition algorithms that run in a reliable manner. The main application receives data from the acquisition module through a local TCP/IP connection. The acquisition module connects to the robot controller through a UDP/IP Ethernet connection and to the UT instrument with a TCP/IP connection.



(a) (b)

FIGURE 1. IntACom robot cell (a) and schematic representation of the robotic inspection procedure (b).

FastSurf has supported the development of the IntACom robotic inspection system prototype and the achievement of the project objectives. However, it has been noticed that there is still room for improvements. It is possible to list a series of limitations of current OLP software:

1. Path-planning for automated NDT inspections is a very specific task. Much commercial software for off-line robot programming draws its origin from the need to use the advantageous flexibility of general robotic manipulators to replace the more traditional and usual machining tools (milling machines, lathes, etc.). As a result, many commercial software applications for off-line programming of robots are expensive tools, incorporating lots of unnecessary functions for CAD/CAM purposes and machining features. Despite the abundance of functions, a tool-path generated via a CAD/CAM commercial software usually has to be subjected to some amendments, before fulfilling all the requirements for an effective NDT inspection. A number of problems are often present in the original path, being generated by software functions expressly developed for machining and production operations rather than for NDT tasks.

2. Significant complications exist when two or more robotic arms need to be synchronized in order to perform a specific NDT inspection. The Ultrasonic Through-Transmission (UTT) technique, for example, uses two transducers: one emitter and one receiver; the receiver being placed on the opposite side of the component and facing the transmitting probe. Currently, many commercial pieces of software (e.g. Delcam and Mastercam) do not offer support for co-operating robots. FastSurf allows partial synchronization of robotic movements (e.g. at start or end points of complex paths), using digital I/O signals, but not full synchronisation over the complete path, required for the UTT technique.

3. Current OLP software lacks fundamental capability in conditional programming. Typically very specific code is generated for each toolpath, and changes to this path due to changing operation conditions requires re-downloading a complete new path to the robot controller. NDT inspection often requires re-inspection of a particular area of interest of a sample in order to carry out more detailed investigation after an initial screening. This requirement places an additional demand of a more adaptive approach to the path planning that has the provision for conditional modification in response to externally measured data.

In summary, OLP is geared towards manufacturing applications where the task is the production of a specific component. The result of an automated NDT inspection is a collection of digital data coming from one or more transducers, and stored in convenient ways. These data results are only meaningful when merged with the precise position of acquisition; in other words, it is necessary to record the current position of the robot throughout the whole inspection time in order to encode the NDT data [6]. Modern industrial robotic arms are equipped with encoders monitoring the position of each joint; they can inform about their position at regular time intervals lasting some milliseconds. The captured positions can be further interpolated to extrapolate the probe's location at the collection time of each piece of NDT information. An external computer (separate to the robot controller) is generally required to process the robot positional data and perform synchronisation to the externally measured NDT data.

Development of MATLAB Based Path-Planning Software

New MATLAB based path-planning software (herewith referred to as *RoboNDT*) was developed from scratch to specifically address the current needs of robotic NDT. The aim is to obtain effective tool-path generation that overcomes the deficiencies of existing off-line programming. Unlike current commercial applications, the new software is being developed around the specific needs of NDT inspections. The fundamental key point supporting this task is the possibility to control industrial robots by an external computer communicating to the robot controllers through an Ethernet connection. If the same computer is used for controlling the robot path and receiving positional feedback, it is clear that a flexible and adaptive approach to path generation can be achieved. RoboNDT aims to be a piece of software capable of off-line path planning and of outputting command coordinates suitable for external control of robot movements. Figure 2 shows the improved inspection procedure enabled by pursuing the new path-planning approach.

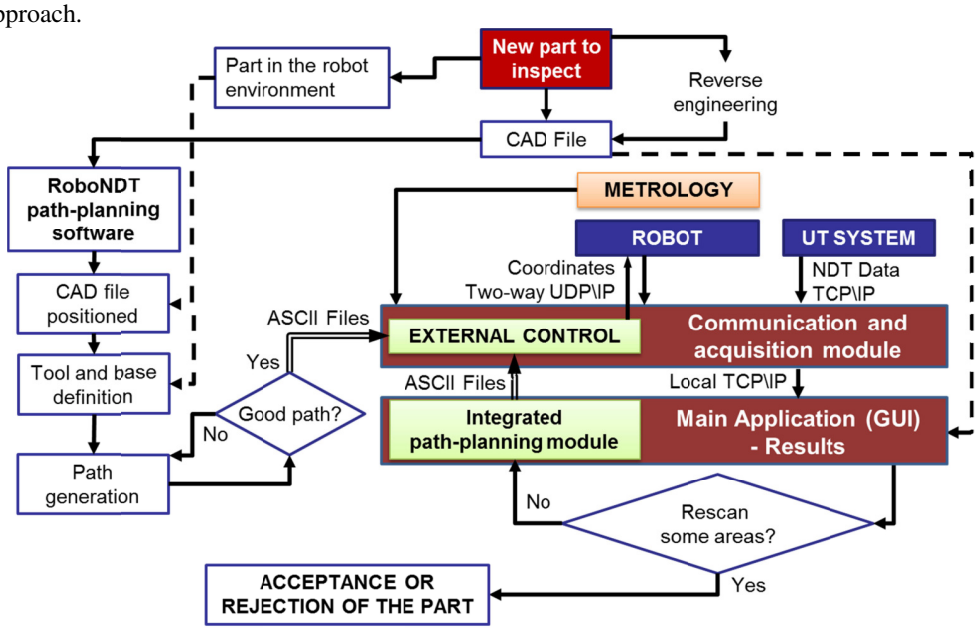


FIGURE 2. Improved inspection procedure enabled by RoboNDT software.

Using the MATLAB based path-planning application instead of commercial software removes the necessity of creating specific robot language programs and allows the generation of packets of command coordinates, suitable to be sent to the robot controller. The previously used one-way UDP/IP communication between the acquisition

module and the robot manipulator is replaced by a two-way connection that allows streaming of the command coordinates, thus controlling the robot tool-path, and reception of robot positional feedback. Since the upgraded acquisition module manages both the robot external control and the reception of feedback coordinates, it paves the way to the integration of metrology. Metrology sensors can easily be interfaced with the software platform to obtain meaningful data for position error monitoring and/or real-time path correction. Moreover, the communication between metrology sensors and the acquisition software can provide a viable pathway towards automatic recognition of the part to inspect and the assessment of its position within the robot working envelope.

RoboNDT software has been organized according to a modular architecture based on four modules: start-up, path-planning, evaluation and output module. For the sake of flexibility, the software contains five libraries. The user can import all the samples and parts of interest into the *Samples Library*. The probes, sensors and tools to be mounted to the robot manipulator can be set into the *Tools Library*. The *Robot Cell Library* can contain multiple robot cells, complete with environment parts and robot manipulators. Separate libraries exist for the environments and the robot models. Any changes made to the robot models in the *Robots Library* or to the environments in the *Environments Library* are automatically transferred to the assembled robot cells defined in the *Robot Cells Library*. Figure 3 shows screenshots of each one of the developed libraries.

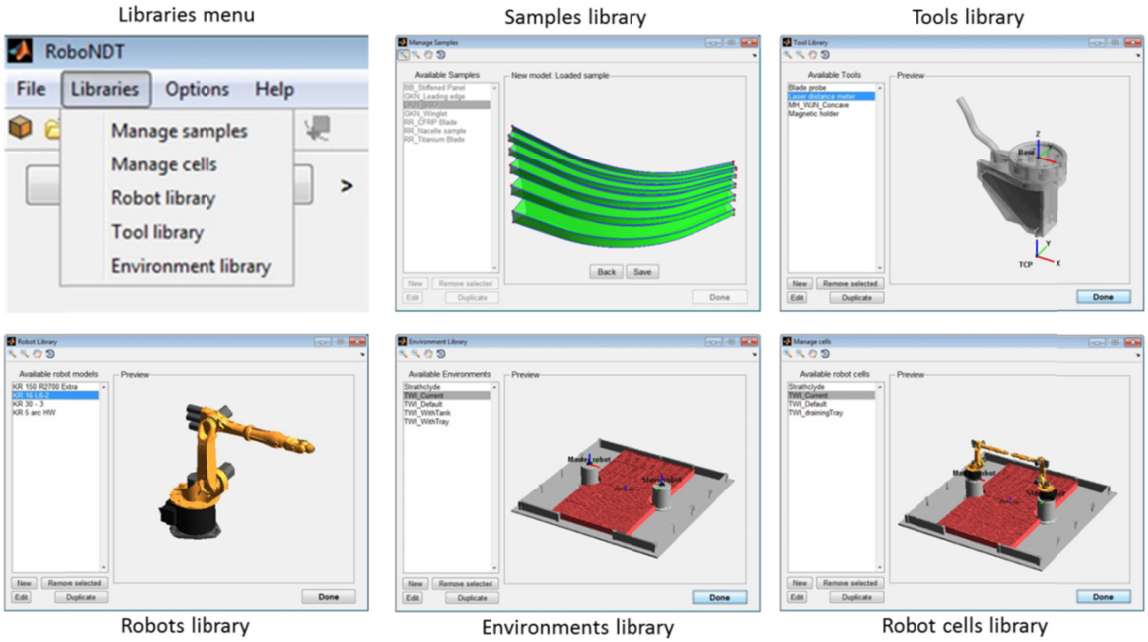


FIGURE 3. Screenshots of the developed libraries.

The *start-up module* of the software is responsible for setting the scene of the path-planning project. The software can import Standard Tessellation Language (STL) CAD files [17]. The STL format was chosen because it is supported by the majority of the existing software packages; it is widely used for rapid prototyping and computer-aided manufacturing. The start-up module allows the calibration of the part of interest within the virtual model of the selected robot cell. The calibration is an interactive procedure; the operator can select up to 10 reference points of the part and insert their positions by jogging the robot Tool Centre Point (TCP) to the real points. The relative coordinates, reported by the robot teach pendant, are transferred into the start-up module.

The *path-planning module* is the core of the software. It contains the necessary algorithms to generate the desired inspection tool-path for each given surface of the part of interest. Three main tool-path types are being implemented: *raster*, *segment* and *single point scan*. Each path type has several characteristic settings that allow a good level of flexibility and customization according to the inspection needs (scanning step, speed, offsets, etc…).

The *evaluation module* provides a full simulation capability of the programmed robot path together with any other CAD components included in the robot cell. The implementation of the full inverse kinematic model of the robotic arms had initially been based on open-source MATLAB code, the KUKA Control Toolbox (KCT) produced by the University of Siena (Italy) in 2011 [18]. However, a fundamental problem was observed with the usage of the KCT. The open-source code does not allow the selection of the robot configuration (a six-axis robot can reach any point within its working envelope in 8 different configurations). This inconvenience made the KCT function unsuitable for use in the new software application that has a target to be as flexible as possible. A new inverse kinematics function, based on a geometric approach, was therefore developed and implemented. Figure 4 presents three snapshots of the recorded simulation video acquired from the RoboNDT software and of the real robot inspection tool-path for a given datum surface. The tool-path is a raster scan with 50 mm pitch, executed at a speed of 100 mm/s. The toolpath simulation of RoboNDT allows accurate time approximation of scanning time.

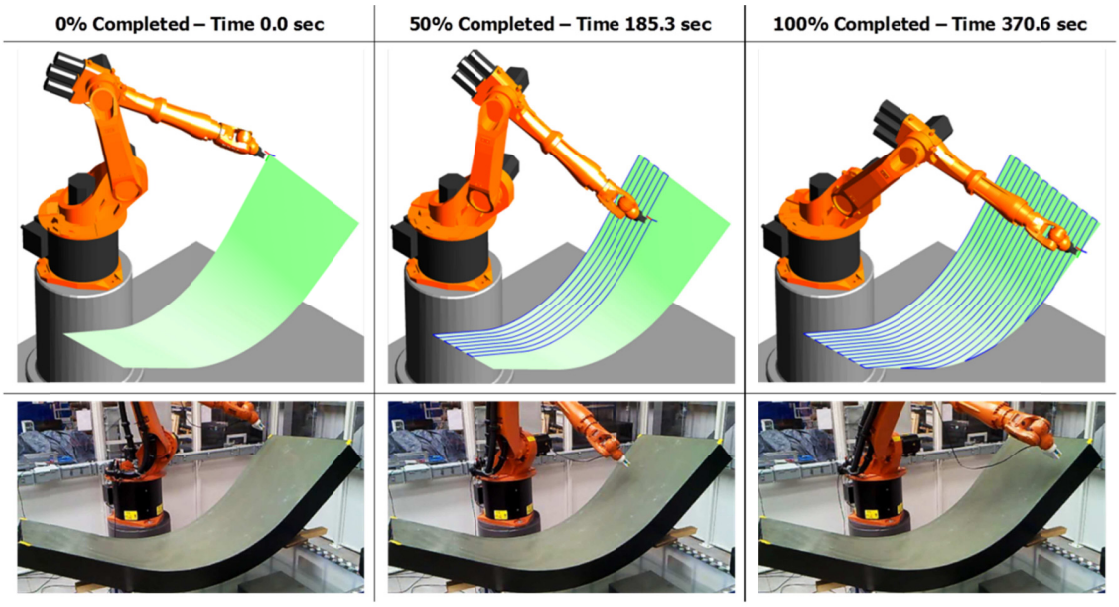


FIGURE 4. Snapshots of the simulation video and of the real inspection tool-path, for the datum surface of the example target surface.

Finally, the output module has been developed to output the results of the computations. Two text files in ASCII format are generated for each tool-path. The first file contains all command coordinates that the robot needs to execute the generated tool-path; the second file contains the necessary points to set the initial and final motion to approach the starting point of the inspection and retract from the endpoint. These two files have very simple syntax; each line merely contains 6 coordinates (x, y, z, A, B, C) to drive the robotic arm to a specific pose. The external control unit, shown by the schema given in Figure 2, imports both files and sends the command data to the robot controller.

The new path-planning approach paves the way to supporting inspection techniques that require multiple robots. The insertion of multiple packets of coordinates in each line of the first command file can become the principle behind multiple robot synchronization. Sending command coordinates simultaneously to multiple robot controllers from the same external server computer enables the path synchronization mismatch to be maintained to the minimum. The maximum misalignment would remain within the distance covered by the robots in a single interpolation cycle. For example, for robots running in a 12 milliseconds interpolation cycle and moving at 100mm/s, the maximum path mismatch would be equal to 1.2 mm. This worst case scenario is much improved over commercial solutions that use digital I/O signals for synchronization purposes.

It is usual for NDT operators to double check some suspect areas of a part, after an initial inspection. For such situations, generating specific tool-paths for all the areas of interest through commercial path-planning software would be time consuming and not very practical. A MATLAB based path-planning module has been purposely

developed to be integrated into the main GUI. The path-planning software add-on is able to use the original tool centre point (TCP) data, received from the robot during the initial scan, in order to generate a specific tool-path for returning to the point of interest and executing what is called a "sub-scan". The original robot trajectory is interpolated to generate the desired type of sub-scan tool-path: raster, segment or single point. Figure 5 shows the simulation of a raster sub-scan, before execution. Therefore the execution of the sub-scan is carried out through controlling the robot arm via the UDP/IP Ethernet connection established by the external control component of the acquisition module.

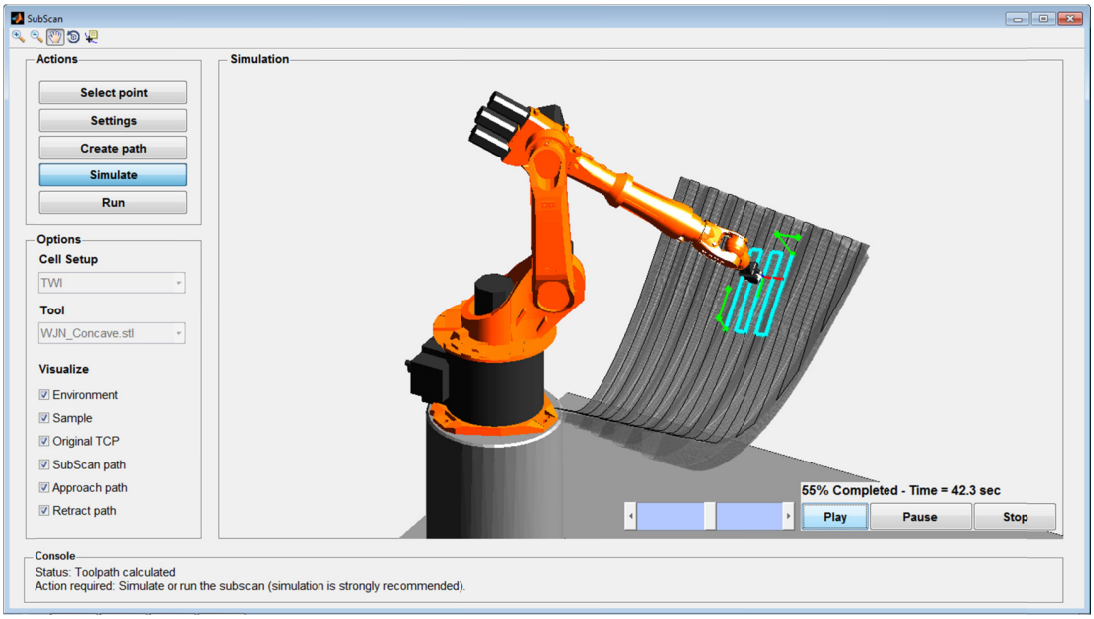


FIGURE 5. Screenshot of the integrated path-planning module during the simulation of the sub-scan tool-path.

VALIDATION EXPERIMENTS – PATH ACCURACY

The IntACom inspection system comprises two KUKA KR16 L6-2 robot arms. The main features of the robot arms are presented in Table 1.

TABLE 1. KUKA KR16 L6-2 principal specifications [19].

	KR16 L6-2
Payload	6 kg
Maximum total load	36 kg
Max. reach	1911 mm
Max. speed	2 m/s
Number of axes	6
Position repeatability	<±0.05 mm
Controller	KR C4
Protection classification	IP 65

To evaluate the accuracy of generated paths from the MATLAB toolbox, a precision non-contact laser distance measurement probe was mounted onto the end effector of one of the two robot arms. An acuity AR200-100 laser distance measurement probe was chosen [20]. The laser distance meter is a metrology device that was integrated into the acquisition module. It was used to continuously monitor the probe separation from the sample surface during a full surface scan. The capability to control the laser sensor via the RS232 serial communication was exploited.

The laser sensor was established as the robot tool, setting its TCP along the laser beam at the central position of the sensor span (according to dimensional specifications of sensor and holder). The selected laser distance meter used triangulation to measure distance. It had a 101.6mm detection span with 79mm standoff to the middle of span

and a resolution of 30.5µm. The measurement laser spot size was smaller than 250µm and the maximum sampling frequency was equal to 1250Hz.

Raster scan paths were generated through the MATLAB based software and used to finely follow the curved contour of the main skin of a carbon fibre composite material aerospace winglet. The surface of interest had an area of 1.6m^2. Three separate tool-paths were generated to travel along equally spaced trajectories (10mm pitch) at constant speeds of 100, 200 and 300mm/s, respectively. The C++ code of the acquisition module transmitted command positions to the robot controller and received actual TCP coordinates over the Ethernet interface within cycles of 12 milliseconds. The sampling rate of the laser sensor was set to 250 Hz, resulting in an average of three data samples for each robot interpolation cycle.

The laser sensor data was mapped to the surface scan by comparing with the interpolated feedback coordinates. Figure 6 shows the recorded maps of difference between measured and theoretical TCP for the three different robot speeds. The results show that the deviation of the measured distance from the theoretical TCP spans a range between ± 2mm.

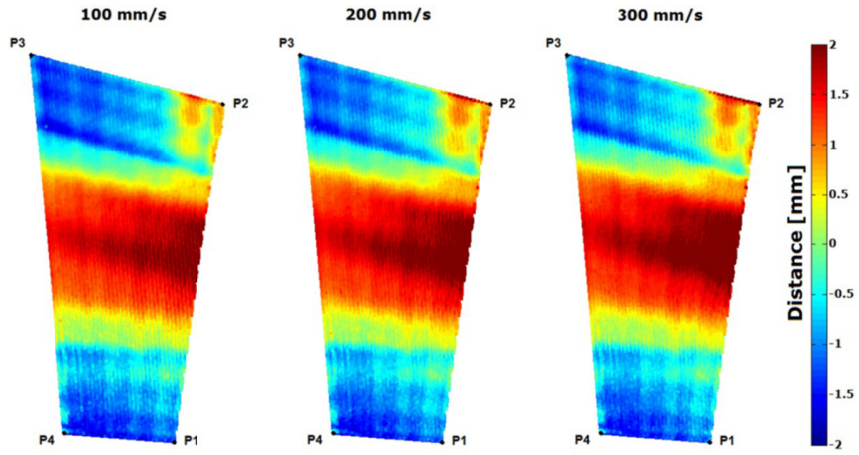


FIGURE 6. Maps showing distance deviation from theoretical TCP for different robot speeds.

During manufacture, as the composite part is removed from the mould, the part can exhibit a spring-back effect due to fibre deviation, residual stress and strain [21]. The difference between the CAD dimensions and the manufactured component can be several millimetres for large composite samples [22] and this was found to be the principal source of error of the experiment.

NDT RESULTS

A scan image of a curved reinforced wing skin, manufactured with introduced flaws, was obtained using the IntACom prototype system and a suitable tool-path generated by the RoboNDT software. The part was scanned using ultrasound pulse-echo phased array inspection through a 5MHz – 64 element probe (0.6 mm pitch).

Figure 7 shows the Time of Flight (TOF) C-Scan of the large curved surface obtained with the prototype inspection system. The IntACom robotic arms deploy end-effectors carrying ultrasonic transducers, mounted into water jet nozzles that provide suitable water columns to support the ultrasonic beams from the probes to the surface of the sample. The standoff between the water jet nozzle and the sample was set to 8mm. The resolution is uniform across the C-scan and equal to 0.6mm. The skin thickness varies across the sample and the stiffeners are clearly seen. The sample contains some tape insert defects, as indicated by the black ovals in figures 7 and 8. The smallest flaw has been sized to be 5mm wide and the biggest 15mm.

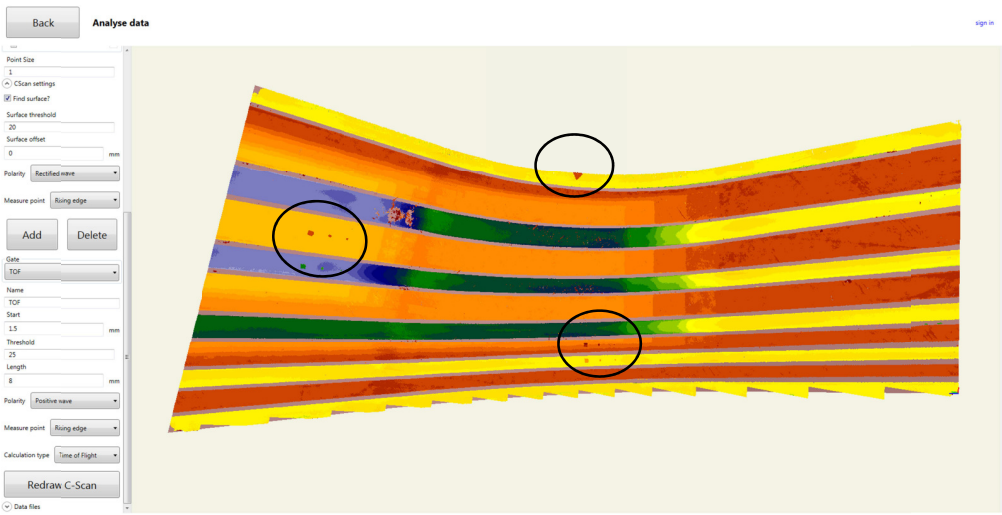


FIGURE 7. C-Scan of the main skin surface of the aerospace composite winglet.

Figure 8 shows a close up of the first group of defects. The GUI of the IntACom software lets the user analyze the collected data through visualization of B-Scans and the A-Scans. The B-Scan is given on the right hand side of the screen; the A-Scan section is at the bottom. The B-Scan is very useful to size the C-Scan features and the potential defects.

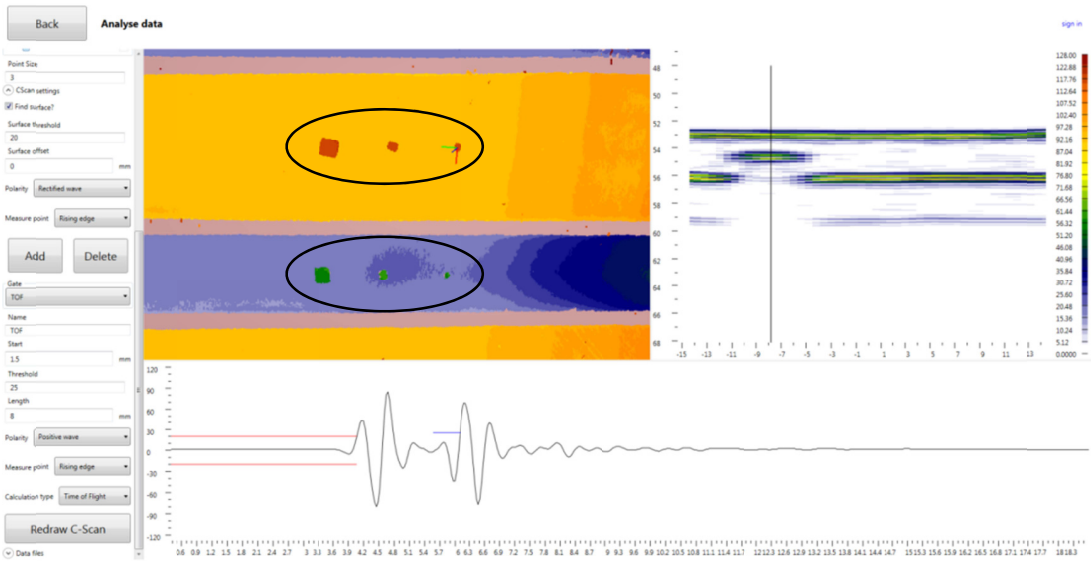


FIGURE 8. Close-up of one of the defected regions.

CONCLUSIONS

In modern aerospace manufacturing, the increasing use of composite materials is introducing new challenges in the inspection and verification procedures required to ensure safe deployment of components in the finished structure. Traditional NDT methods such as ultrasonic testing are fundamental to such inspection. However the complex part shapes employed in aerospace structures, combined with complex material properties of composites, present significant challenges. Traditional manually delivered NDT is time consuming and manufacturers are increasingly demanding reduced cycle times for the inspections undertaken. Although some part geometries lend themselves to bespoke Cartesian or Cartesian plus rotation stage mechanical scanners, there are many instances of

complex geometry that make the use of 6 axis robot positioners highly attractive. Most existing off line programming approaches are geared towards manufacturing processes, and lack the required flexibility for application to delivery of NDT measurements. In particular the lack of conditional programming capability has been identified as one of the key shortcomings in existing software. This is fundamentally important for 2 reasons. Firstly composites manufacturing has higher part variability and deviation from CAD than encountered with traditional materials. Secondly NDT processes often require local measurement refinement. These shortcomings have motivated the authors to develop new MATLAB based robotic programming software specifically geared towards NDT path planning applications.

The new software has been tailored to the generation of raster scan paths for inspection of curved surfaces by 6-axis industrial robots, and in its current form represents the first iteration of a system designed to overcome the issues with current OLP packages. The software is intended to be flexible and extensible to future systems and robot developments. The output tool-path is not specific to robot programming language or hardware, so could be deployed across a range of platforms. It has been explained how the execution of the calculated path by a robotic arm, externally controlled through a C++ external control unit, can be beneficial for NDT inspections. The developed NDT robot toolbox will ultimately assist NDT technicians to move from a component CAD file to the actual physical inspection, without the need to use multiple pieces of software not optimized for robotic NDT inspections. The commercial driver for this work is the need to increase NDT inspection throughput. This has been identified clearly as a bottleneck in existing composite parts manufacture in aerospace industries. The new software will contain specific functions tailored to generate several types of tool-paths for raster scans, segment scans or single point inspections. The inclusion of an evaluation module, incorporating the inverse kinematics, allows the user to have a real-time preview of the calculated path for a successive safe execution in the real robotic environment.

Comparative metrology experiments have been undertaken to evaluate the real path accuracy of the toolbox when inspecting a curved 1.6 m^2 surface using a KUKA KR16 L6-2 robot. The results obtained via a precision laser range meter have shown that the deviation of the distance between the theoretical TCP and a large aerofoil curved surface spans a range between ± 2mm; the dominant source of this error being the deviation of the part from the CAD model. For the current NDT application, this level of accuracy is sufficient as the intended NDT delivery is accomplished using a water jet coupling approach. However more demanding NDT inspection requiring higher path accuracy will demand individual component surface metrology measurement prior to NDT inspection.

In the future a fully developed software solution will support different types of robotic arm and robotic environments. Additionally, the possibility to define custom robotic cells and equip the robotic end-effector with several different probes is the aim for a more versatile software platform for robot deployed NDT. The ultimate goal of the authors remains the simultaneous management of command coordinates, robot positional feedback and NDT data by an integrated server application running on an external computer. This paves the way for the introduction of intelligent novelty factors for the application of robotic NDT inspections. On-line monitoring and data visualization, real-time path correction and versatile path amending approaches are just some of the possible opportunities.

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